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Reliability analysis of soil liquefaction based on standard penetration: a case study in Babol city

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Abstract— **There are more probabilistic and deterministic liquefaction evaluation procedures in order to judge whether liquefaction will occur or not. A review of this approach reveals that there is a need for a comprehensive procedure that accounts for different sources of uncertainty in liquefaction evaluation. In fact, for the same set of input parameters, different methods provide different factors of safety and/or probabilities of liquefaction. To account for the different uncertainties, including both the model and measurement uncertainties, reliability analysis is necessary. This paper has obtained information from Standard Penetration Test (SPT) and some empirical approaches such as: Seed et al, Highway bridge of Japan approach to soil liquefaction, The Overseas Coastal Area Development Institute of Japan (OCDI) and reliability method to studying potential of liquefaction in soil of Babol city in the north of Iran are compared. Evaluation potential of liquefaction in soil of Babol city is an important issue since the soil of some area contains sand, seismic area, increasing level of underground waters and consequently saturation of soil; therefore, one of the most important goals of this paper is to gain suitable recognition of liquefaction potential and find the most appropriate procedure of evaluation liquefaction potential to decrease related damages.**

Index Terms— liquefaction, safety factor, Standard Penetration Test, reliability, soil

I. Introduction

Liquefaction of soil is one of the most important and complicated topics of seismic geo-technique engineering in which soil is turned into fluid due to being treated with 3 modes including: sediments or grain embankment, saturation by underground water and powerful tremble. One of the most important harmful effects of liquefaction is eliminating the loading capacity of foundation, soil settlement, density of liquefaction layers, boiling sand and projection from inside of bulky deep buried structures, deformation or lateral development. Civil engineers usually use a factor of safety (FS) to evaluate the safety of a structure [1] [2]. The safety factor is defined as the strength of a member divided by the load applied to it. Most design codes require that a member's calculated safety factor should be greater than a specified safety factor, a value at least larger than one, to ensure the safety of the designed structure. Since the specified safety factor is largely determined by experience, there has been no rational way to determine such a factor up to now. Because the safety factor-based design method does not account for the variability of the member strength or the applied loading, the probability that the structure will fail cannot be known. Simplified procedures, originally proposed by Seed and Idriss [3], using the standard penetration test (SPT) [4], are frequently used to evaluate the liquefaction potential of soils. The procedure has been revised and updated since its original development. The method was developed from field liquefaction performance cases at sites that had been characterized with in situ standard penetration tests. Using a deterministic method, liquefaction of soil is predicted to occur if the factor of safety (FS), which is the ratio of the cyclic resistance ratio (CRR) over cyclic stress ratio (CSR), is less than or equal to one. No soil liquefaction is predicted if FS $\geq$ 1.In the proposed method in regulation of Japan's marine, compilation of methods based on outdoor tests and laboratory is used for Liquefaction potential [5].

Reliability calculations provide a means of evaluating the combined effects of uncertainties and provide a logical framework for choosing factors of safety that are appropriate for the degree of uncertainty and the consequences of failure[6][7]. Thus, as an alternative or a supplement to the deterministic assessment, a reliability assessment of liquefaction potential seems to be useful in making better engineering decisions. Recently Hwang et al [8] have conducted an analysis that quantifies uncertainties in the CSR and CRR. In their analysis, the uncertainties in the CSR and CRR are represented in terms of corresponding probability density functions. The probability density function (PDF) of CSR is obtained based on a first order second moment (FOSM) [9] method while the PDF of CRR is obtained from the first derivative of the CRR function, which is based on a logistic regression analysis of data about earthquakes occurring in the past. However, the PDF of CRR does not account for the uncertainty in SPT resistance that arises from inherent test errors induced even when the specified standards are carefully observed. Thus, it is necessary to use a PDF of CRR that accounts for uncertainties in SPT

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resistance in order to quantify its effects on liquefaction reliability.

II.SEED ET AL APPROACH FOR SOIL LIQUEFACTION

For liquefaction evaluation, the cyclic stress ratio (CSR) has been proposed by Seed et al [2].

$$CSR = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\delta_v}{\delta_v^{'}}\right)r_d \quad (1)$$

Where σ_v is the total vertical stress; $\sigma_v^{'}$ is the effective vertical stress; $a_{\max}$ is the peak horizontal ground surface acceleration; g is the acceleration of gravity; and r_d is the nonlinear shear stress mass participation factor (or stress reduction factor). The term r_d provides an approximate correction for flexibility in the soil profile. There are several empirical relations [9] [10] relating r_d with depth and other parameters, the summary of which can be found in Cetin and Seed [11]. The earliest and most widely used recommendation for assessment of r_d was proposed by Seed and Idriss [1], approximated by Liao and Whitman [12], and expressed in [13] as

$$r_d = \frac{\left(1 - 0.4113Z^{0.5} + 0.04052Z + 0.001753Z^{1.5}\right)}{\left(1 - 0.4177Z^{0.5} + 0.05729Z - 0.006205Z^{1.5} + 0.001210Z^{2}\right)} \quad (2)$$

Where z is the depth below ground surface in meters. Cyclic resistance ratio (CRR), the capacity of soil to resist liquefaction, can be obtained from the corrected blow count $(N_1)_{60}$ using empirical correlations proposed by Seed et al [2]. CRR curves have been proposed for granular soils with fines contents of 5% or less, 15%, and 35% and are only valid for magnitude 7.5 earthquakes. The CRR curves for a fines content of <5% (clean sands) can be approximated by [3]

$$CRR_{7.5} = \frac{1}{34 - (N_1)_{60}} + \frac{(N_1)_{60}}{135} + \frac{50}{\left[10(N_1)_{60} + 45\right]^2} - \frac{1}{200} \quad (3)$$

For $(N_1)_{60} \langle 30$, for $(N_1)_{60} \rangle 30$, clean granular soils are classified as non-liquefiable. The CRR increases with increasing fines content [3] and thus $(N_1)_{60}$ should be corrected to an equivalent clean sand value $(N_1)_{60}$. The factor of safety (FS) against liquefaction in terms of CSR and CRR is defined by

$$F = \frac{CRR_{7.5}}{CSRN} \quad (4)$$

Where CSRN is the normalized CSR for earthquakes of magnitude 7.5(CSR/MSF) [22] [23]; MSF is the magnitude scaling factor. The term MSF is used to adjust the calculated CSR or CRR to the reference earthquake magnitude of 7.5. An assessment of liquefaction potential can readily be made by Eq. (4). Liquefaction is predicted to occur if FS < 1, and no liquefaction is predicted if FS > 1[17].

In the following, the liquefaction potential for three bore logs related to three parts of Babol city which are presented here using Seed at al approach. The typical bore log data from a site located at Amirkabir intersection, Motahary Avenue, Modares avenue is shown in Table 1, 2 and 3, respectively. A liquefiable sandy layer exists from a depth of 4–14 m. The water table is at a depth of 1. 5 m. The site has been analyzed for $a_{\max} = 0.3g$, and Mw = 7.5. The different factors of safety in the range of 0.24–2.4 are obtained for the same input parameters.

TABLE I. THE TYPICAL BORE LOG DATA AT AMIRKABIR- BABOL

Fs	CSR	CRR	(N1)60	Fc (%)	$\sigma_v^{'}$ (N/m^3)	σ_v (N/m^3)	γ $(N/m)^3$	Depth (m)
0.46	0.38	0.18	6	78.3	19	38.6	19.3	2
0.24	0.41	0.10	4	78.3	33.2	72.4	18.1	4
0.33	0.37	0.12	7	100	57.6	116.4	19.4	6
0.41	0.35	0.14	10	52.5	80	158.4	19.8	8
0.37	0.37	0.13	12	3.1	88	186	18.6	10
0.59	0.33	0.2	20	4.2	114	231.6	19.3	12
0.58	0.31	0.18	20	4.2	133	270.2	19.3	14
0.79	0.27	0.21	21	100	161.6	318.4	19.9	16
0.76	0.24	0.19	20	100	189	365.4	20.3	18
0.86	0.22	0.19	22	81.9	216	412	20.6	20
0.83	0.21	0.18	21	100	235.4	451	20.5	22
0.95	0.21	0.2	24	100	245	490	19.6	25

Fs	CSR	CRR	$(N_1)_{60}$	Fc (%)	σ'_v (N/m^3)	σ_v (N/m^3)	γ $(N/m)^3$	Depth (m)
2.4	0.41	1.0	11	80.6	16.8	36.4	18.2	2
1.0	0.40	0.41	14	81.7	34.4	73.6	18.4	4
0.56	0.38	0.21	12	81.1	53.4	112.2	18.7	6
0.45	0.37	0.17	11	80.7	72	150.4	18.8	8
0.49	0.37	0.18	13	79.1	86	184	18.4	10
1.35	0.35	0.48	25	78.2	102	219.6	18.3	12
0.92	0.32	0.30	23	76.7	120.4	257.6	18.4	14
0.44	0.28	0.17	12	5	55.2	114	19	6
0.37	0.38	0.10	9	75.3	150.4	307.2	19.2	16
0.34	0.28	0.13	8	65	69.6	148	18.5	8
0.73	0.35	0.19	18	18.7	174.6	351	19.5	18
0.68	0.25	0.24	15	29	94	192	19.2	10
0.73	0.34	0.17	17	20.6	196.8	388.4	19.4	20
0.53	0.24	0.18	12	25	[illegible]	[illegible]	18.7	12
0.72	0.32	0.16	16	21.3	215.6	431.2	19.6	22
0.28	0.20	0.08	7	10	142.8	280	20	14
0.75	0.32	0.16	11	26.2	223.2	458.4	19.1	24
0.38	0.22	0.12	10	97	120	276.8	17.3	16
0.50	0.30	0.15	13	92	129.6	306	17	18

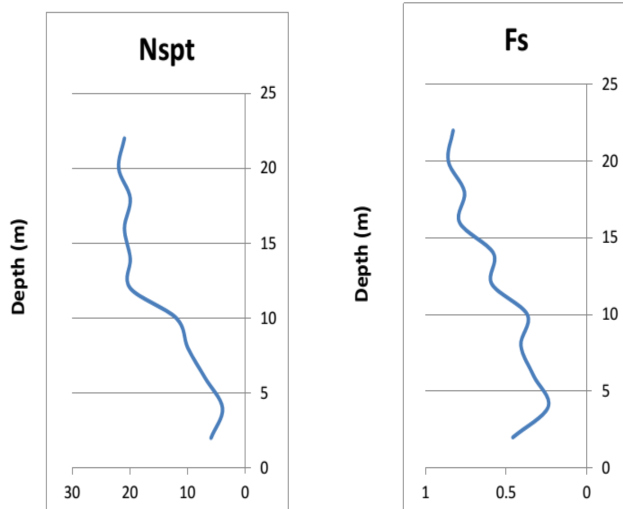


Figure 1. Liquefaction potential evaluation related to Amirkabirbor log

TABLE II. THE TYPICAL BORE LOG DATA AT MOTAHARY- BABOL

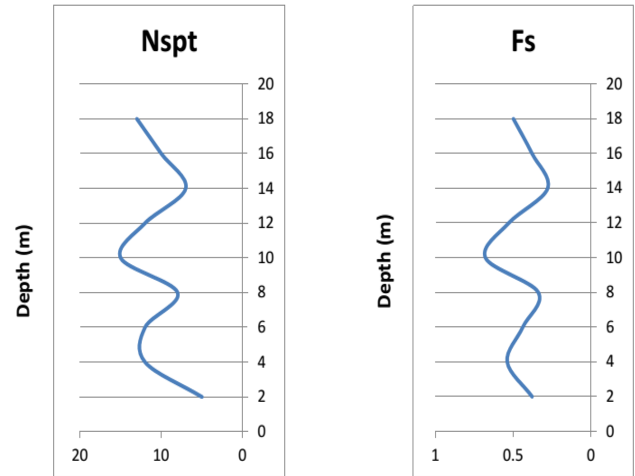


Figure 2. Liquefaction potential evaluation related to Motahary bore log

TABLE III. THE TYPICAL BORE LOG DATA AT MODARES- BABOL

Fs	CSR	CRR	$(N_1)_{60}$	Fc (%)	σ'_v (N/m^3)	σ_v (N/m^3)	γ $(N/m)^3$	Depth (m)
0.38	0.43	0.16	5	80	15.4	35	17.5	2
0.54	0.41	0.22	12	5	32.8	72	18	4

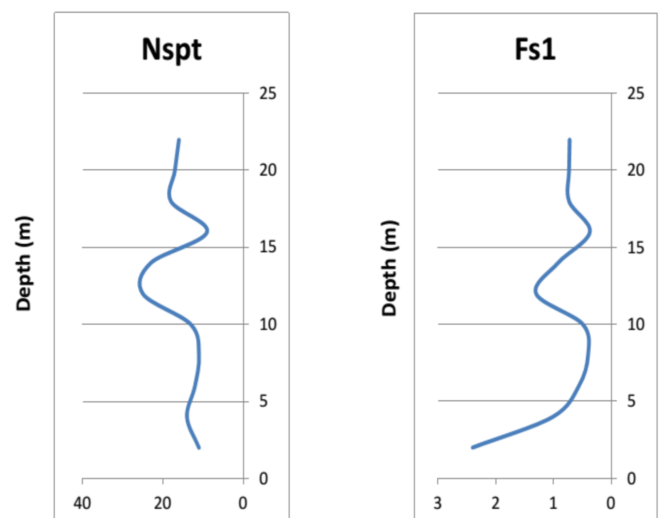


Figure 3. Liquefaction potential evaluation related to Modares bore log

III. OCDI FOR APPROACH SOIL LIQUEFACTION

As Prediction of liquefaction using equivalent N-values for the subsoil with a gradation that falls within the range

“possibility of liquefaction”, further investigations should be carried by the descriptions below.

Equivalent N-value

The equivalent N-value should be calculated from equation

$$(N_1)_{60} = \frac{N - 0.019(\sigma_v' - 65)}{0.0041(\sigma_v' + 65) + 1.0} \quad (5)$$

Where

N_{65}: Equivalent N-value

N: N-value of the subsoil

σ_v' : Effective overburden pressure of the subsoil (KN/m^2)

The equivalent N-value refers to the N-value corrected for the effective overburden pressure of 65 KN/m^2. This conversion reflects the practice that liquefaction prediction was previously made on the basis of the N-value of a soil layer near a groundwater surface [16].

2-Equivalent acceleration

The equivalent acceleration should be calculated using equation (2)

$$A_{eq} = 0.7 \frac{\tau_{max}}{\sigma_v'} g \quad (6)$$

Where

A_{eq} : Equivalent acceleration (Gal)

τ_{max} : Maximum shear stress (KN/m^2)

σ_v' : Effective overburden pressure (KN/m^2)

G: gravitational acceleration (980 Gal)

3-Predictions using the equivalent N-value and equivalent acceleration:

The soil layer should be classified according to the ranges labeled I ~ IV in Fig. 4, using the equivalent N-value and the equivalent acceleration of the soil layer. The meaning of the ranges I ~ IV is explained in Table 4.

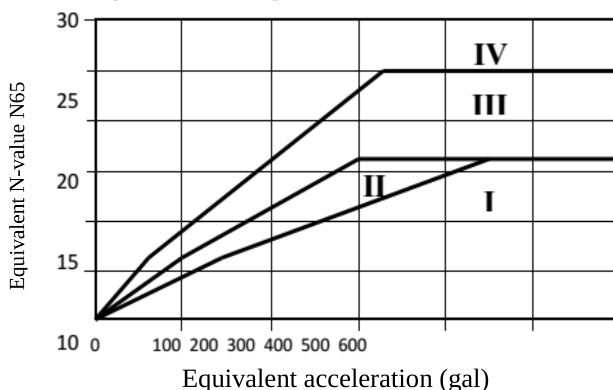


Figure 4. Classification of Soil Layer with Equivalent N-Value and Equivalent Acceleration

Correction N-values and predictions when the fraction of fines content is relatively large.

When the fines content (grain size is 75 _m or less) is 5% or greater, the equivalent N-value should be corrected before applying Fig. 4. Corrections of the equivalent N-value are divided into the following three cases.

Case 1: when the plasticity index is less than 10 or cannot be determined, or when the fines content is less than 15% The equivalent N-value (after correction) should be set as $(N)_{65}/Cn$. The compensation factor Cn is given in Fig4. The equivalent N-value (after correction) and the equivalent acceleration are used to determine the range in Fig.5.

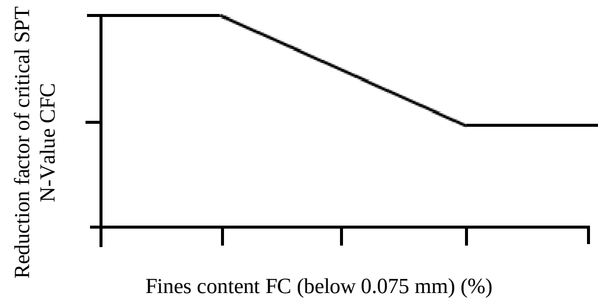


Figure 5. Compensation Factor of Equivalent N-Value Corresponding to Fine Contents

Case 2: when the plasticity index is greater than 10 but less than 20, and the fines content is 15% or higher The equivalent N-value (after correction) should be set as both (N)65/0.5, and N + _N, and the range should be determined according to the following situations, where the value for _N is given by the following equation:

$$\Delta N_{60} = 8 + 0.45(I_p - 10) \quad (7)$$

1) When N + _N falls within the range I, use range I.
2) When N + _N fall within the range II, uses range II.
3) When N +_N falls within the range III or IV and $(N_{65})/0.5$ is within range I, II or III, use range III.
4) When N + _N falls within range III or IV and $(N_{65})/0.5$ is within range IV, use range IV.

Here, the range III is used for the case iii) even when the equivalent N-value (after correction) with $(N_{65})/0.5$ is in the range I or II, because the results from the fines content correction are too conservative. The reason that the range IV is not used for the case iii) even when range IV is given by a correction N + _N is that the reliability of the plasticity index in the equation is low when the value is 10 ~ 20. Therefore, judging the subsoil as the range IV “possibility of liquefaction is very low” is considered as risky.



Case 3: when the plasticity index is 20 or greater, and the fines content is 15% or higher

The equivalent N-value (after correction) should be set as N + _N. The range should be determined according to the equivalent N-value (after correction) and the equivalent acceleration.

Liquefaction predictions

Since liquefaction predictions must also consider the factors other than physical phenomena such as what degree of safety should be maintained in the structures, it is not possible to unconditionally establish any criterion for judgments regarding various prediction results. The rule of judgment of liquefaction occurrence for the results of prediction that is considered as standard is listed in Table 4.

In this table, the term “prediction of liquefaction” refers to the high or low possibility of liquefaction as a physical phenomenon. In contrast, the term “judgment of liquefaction” refers to the consideration of the high or low possibility of liquefaction and judgment of whether or not the ground will liquefy.

TABLE IV. PREDICTIONS AND JUDGMENTS OF LIQUEFACTION FOR SOIL LAYER ACCORDING TO RANGES I TO IV

Range shown in Fig.4	Prediction of liquefaction	Judgment of liquefaction
I	Possibility of liquefaction occurrence is very high	liquefaction will occur
II	Possibility of liquefaction occurrence is high	Either to judge that liquefaction will occur or to conduct further evaluation based on cyclic triaxle tests.
III	Possibility of liquefaction is low	Either to judge that liquefaction will not occur or to conduct further evaluation based on cyclic triaxle tests. For a very important structure, rather to judge that liquefaction will or to conduct further evaluation based upon cyclic triaxle tests.
IV	Possibility of liquefaction is very low	liquefaction will not occur

In the following, the liquefaction potential for three bore logs related to three parts of Babol city which are presented here using Seed at al approach. The typical bore log data from a site located at Amirkabir intersection, Motahary Avenue, Modares avenue is shown in Table 5, 6 and 7, respectively. A liquefiable sandy layer exists from a depth of 4–14 m. The water table is at a depth of 1. 5 m.

TABLE V. THE TYPICAL BORE LOG DATA AT AMIRKABIR- BABOL

Area	A (eq)	N**65	$(N_1)_{60}$	Fc (%)	σ'_v (N/m^3)	σ_v (N/m^3)	γ $(N/m)^3$	Depth (m)
3	419	21.15	6	78.3	19	38.6	19.3	2
3	447	19.15	4	78.3	33.2	72.4	18.1	4
1	600	12.07	7	100	57.6	116.4	19.4	6
3	387	21.46	10	52.5	80	158.4	19.8	8
1	401	10.68	12	3.1	88	186	18.6	10
3	363	16.04	20	4.2	114	231.6	19.3	12
2	338	14.8	20	4.2	133	270.2	19.3	14
4	298	29	21	100	161.6	318.4	19.9	16
4	268	30	20	100	189	365.4	20.3	18
4	244	29	22	81.9	216	412	20.6	20
4	233	29	21	100	235.4	451	20.5	22
4	227	30	24	100	245	490	19.6	25

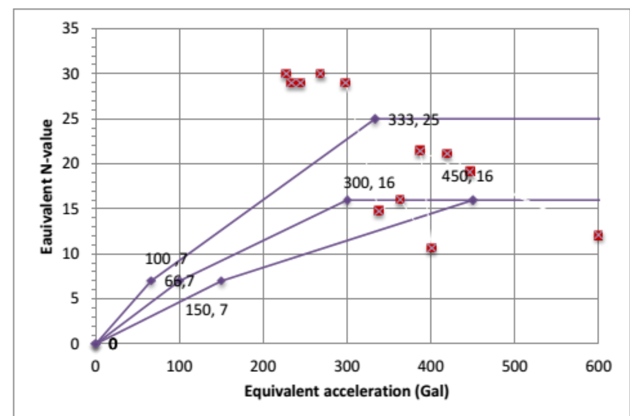


Figure 6. Classification of Soil Layer related to Amirkabir bore log

TABLE VI. CLASSIFICATION OF SOIL LAYER RELATED TO MOTAHARY BORE LOG

Area	A (eq)	N**65	$(N_1)_{60}$	Fc (%)	σ'_v (N/m^3)	σ_v (N/m^3)	γ $(N/m)^3$	Depth (m)
3	471	16.15	5	80	15.4	35	17.5	2
1	450	14.6	12	5	32.8	72	18	4
1	41	12.7	12	5	55.2	114	19	6



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3	41 7	19.1 5	8	65	69.6	148	18.5	8
2	38 7	15	15	29	94	192	19.2	10
1	37 6	12	12	25	106. 8	224. 4	18.7	12
1	32 5	5	7	10	142. 8	280	20	14
3	35 2	23.4	10	97	120	276. 8	17.3	16
3	33 0	26.8 5	13	92	129. 6	306	17	18

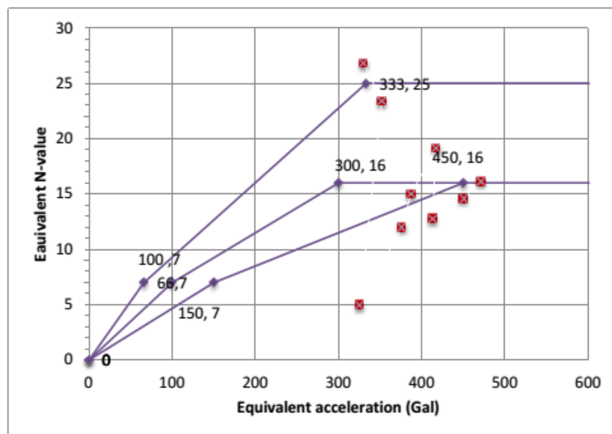


Figure 7. Classification of Soil Layer related to Motahary bore log

TABLE VII. THE TYPICAL BORE LOG DATA AT MODARES- BABOL

Area	A (eq)	N**65	$(N_1)_{60}$	Fc (%)	σ'_v (N/m^3)	σ_v (N/m^3)	γ $(N/m)^3$	Depth (m)
4	44 8	29.7 8	11	80. 6	16.8	36.4	18.2	2
4	43 8	26.2 7	14	81. 7	34.4	73.6	18.4	4
4	42 1	25.8 4	12	81. 1	53.4	112. 2	18.7	6
4	54 6	26.1 8	11	80. 7	72	150. 4	18.8	8
3	40 6	23.4 5	13	79. 1	86	184	18.4	10
4	38 6	30	25	78. 2	102	219. 6	18.3	12
4	35 8	30	23	76. 7	120. 4	257. 6	18.4	14
1	31 0	9	9	75. 3	150. 4	307. 2	19.2	16
4	27 9	22.2 8	18	18. 7	174. 6	351	19.5	18
3	25 9	17	17	20. 6	192	388	19.4	20

3	24 4	16	16	21. 3	215. 6	431. 2	19.6	22
3	23 8	15	11	26. 2	223. 2	458. 4	19.1	24

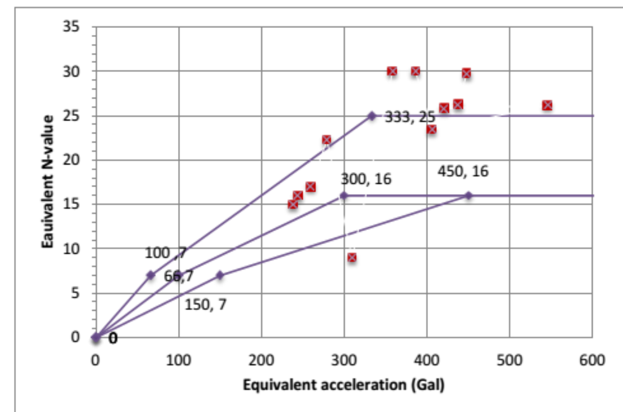


Figure 8. Classification of Soil Layer related to Modares bore log

IV. HIGHWAY RIDGE OF JAPAN APPROACH FOR SOIL LIQUEFACTION

In this approach, a combination of outdoor test method and test is utilized to estimate the potential of liquefaction. The process of this approach is as follows:

1. Exposed soil liquefaction consists of the following:
   a. The water table is smaller than 10 m
   b. The depth of Susceptible to liquefaction layer is less than 20 m
   c. Gravel soil with D50higher than 2mm can liquefy
   d. D50<10mm and D10<1mm
2. The next stage of evaluating the potential of liquefaction is to calculate the cycle stress (CSR)

Then we can calculate the cycle resistance ration (CRR) that results in.8 liquefaction resistance (RL)

$$RL=\begin{cases}0.0882\sqrt{\frac{N_a}{1.7}}N_a\langle 14\\ 0.0882\sqrt{\frac{N_a}{1.7}}\times 1.6\times 10^{-6}(N_a-14)^{4.5}N_a\geq 14\end{cases} \quad (8)$$

In this formula N_a: define for sandy soils (clean sandy, silt sandy, silt) the $N_a=aN_1+b$ and the standard penetration is revised with this formula:

$$N_1=\frac{1.7N}{\sigma'_v\left(\frac{kg}{cm^2}\right)+0.7} \quad (9)$$

Then Coefficients of a and b designation for modifying number of fine on base of the percentage of Fine-grained soil is as follows**:**

TABLE VIII. THE TYPICAL BORE LOG DATA AT AMIRKABIR- BABOL

Fs2	CSR	Rl	Na	$(N_1)_{60}$	Fc (%)	σ'_v (N/m^3)	σ_v (N/m^3)	γ $(N/m)^3$	Depth (m)
0.02	0.38	0.01	15.4	6	78.3	19	38.6	19.3	2
0.49	0.41	0.20	8.87	4	78.3	33.2	72.4	18.1	4
0.01	0.56	0.01	15.8	7	100	57.6	116.4	19.4	6
0.47	0.35	0.16	6.06	10	52.5	80	158.4	19.8	8
0.27	0.37	0.10	2.19	12	3.1	88	186	18.6	10
0.34	0.33	0.11	2.88	20	4.2	114	231.6	19.3	12
0.34	0.31	0.10	2.48	20	4.2	133	270.2	19.3	14
0.92	0.27	0.24	13.6	21	100	161.6	318.4	19.9	16
0.97	0.24	0.23	12.0	20	100	189	365.4	20.3	18
1.03	0.2	0.20	9.27	22	81.9	216	412	20.6	20
1.06	0.21	0.22	11	21	100	235.4	451	20.5	22
1.15	0.2	0.23	11.6	24	100	245	490	19.6	25

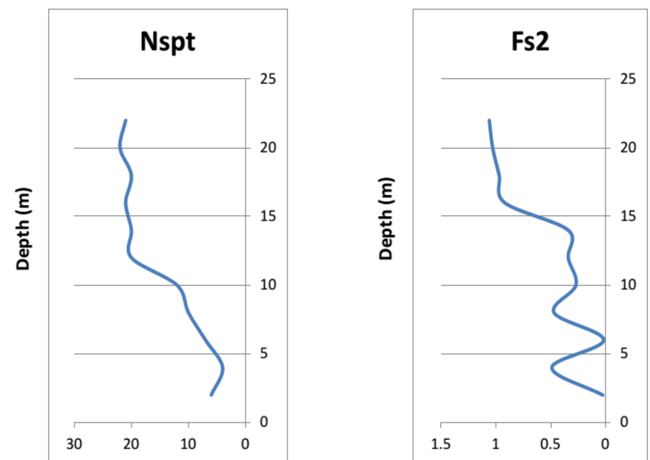


Figure 9. Liquefaction potential evaluation related to Amirkabir bore log

TABLE IX. THE TYPICAL BORE LOG DATA AT MOTAHARY- BABOL

Fs2	CSR	Rl	Na	$(N_1)_{60}$	Fc (%)	σ'_v (N/m^3)	σ_v (N/m^3)	γ $(N/m)^3$	Depth (m)
0.002	0.43	0.01	15.47	5	80	15.4	35	17.5	2
0.37	0.41	0.15	5.23	12	5	32.8	72	18	4
0.32	0.38	0.12	3.34	12	5	55.2	114	19	6
0.47	0.38	0.18	7.13	8	65	69.6	148	18.5	8
0.41	0.35	0.14	4.61	15	29	94	192	19.2	10
0.35	0.34	0.12	3.22	12	25	106.8	224.4	18.7	12
0.20	0.3	0.06	0.80	7	10	142.8	280	20	14
0.67	0.32	0.21	10.1	10	97	120	276.8	17.3	16
0.	0.	0.	10	13	92	129.6	306	17	18



73	3	21	.5						

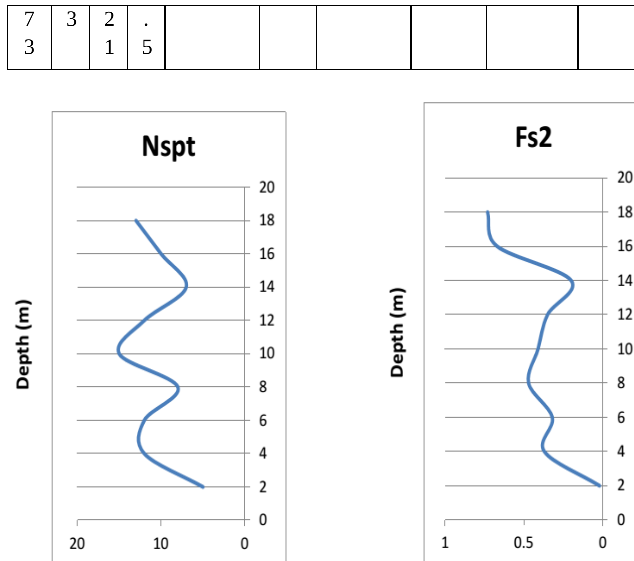


Figure 10. Liquefaction potential evaluation related to Motahary bore log

TABLE X. THE TYPICAL BORE LOG DATA AT MODARES–BABOL

Fs2	CSR	Rl	Na	$(N_1)_{60}$	Fc (%)	σ'_v (N/m^3)	σ_v (N/m^3)	γ $(N/m)^3$	Depth (m)
0.24	0.41	0.09	28.5	11	80.6	16.8	36.4	18.2	2
0.01	0.4	0.07	22.3	14	81.7	34.4	73.6	18.4	4
0.66	0.39	0.25	14.5	12	81.1	53.4	112.2	18.7	6
0.02	0.5	0.01	16.0	11	80.7	72	150.4	18.8	8
0.6	0.37	0.22	11.0	13	79.1	86	184	18.4	10
0.002	0.35	0.001	15.39	25	78.2	102	219.6	18.3	12
0.72	0.33	0.24	12.6	23	76.7	120.4	257.6	18.4	14
0.65	0.28	0.18	6.37	9	75.3	150.4	307.2	19.2	16
0.41	0.26	0.10	2.50	18	18.7	174.6	351	19.5	18
0.43	0.24	0.10	2.38	17	20.6	192	388	19.4	20
0.45	0.22	0.09	2.15	16	21.3	215.6	431.2	19.6	22
0.49	0.21	0.10	2.40	11	26.2	223.2	458.4	19.1	24

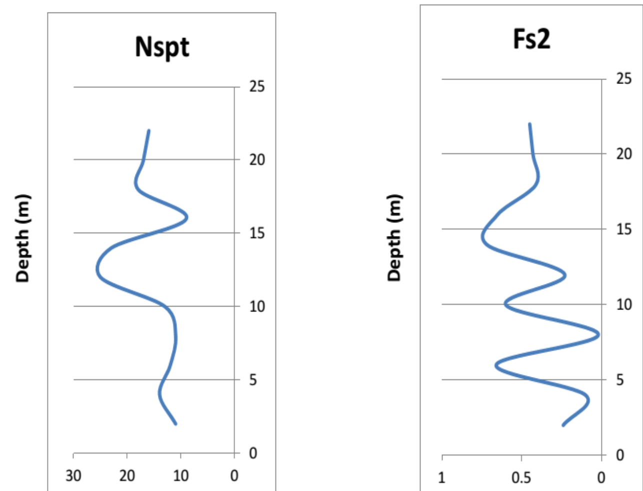


Figure 11. Liquefaction potential evaluation related to Modares bore log

V.RELIAILTY MODEL FOR SOIL LIQUEFACTION

The first step in engineering reliability analysis is to define the performance function of a structure. If the performance function values of some parts of the whole structure exceed a specified value under a given load, it is thought that the structure will fail to satisfy the required function. This specified value (state) is called the limit state of the performance function of the structure. In the Simplified liquefaction potential assessment methods, if the CSR is denoted as S; and the CRR is denoted as R; we can define the performance function for liquefaction as $Z = R - S$. If $Z = R - S \langle 0$, the performance state is designated as 'failed', i.e. liquefaction occurs. If $Z = R - S \rangle 0$, the performance state is designated as 'safe', i.e. no liquefaction occurs. If $Z = R - S = 0$, the performance state is designated as a 'limit state', i.e. on the boundary between liquefaction and non-liquefaction states. Since there are some inherent uncertainties involved in the estimation of the CSR and the CRR, we

can treat R and S as random variables; hence the liquefaction performance function will also be a random variable. Therefore, the above three performance states can only be assessed as have some probability of occurrence. The liquefaction probability is defined as the probability that $Z = R - S \langle 0$. However, an exact calculation of this probability is not easy. In reality, it is difficult to accurately find the PDFs of random variables, such as R and S. Moreover, the calculation of the probability of Z=R-S<0 needs multiple integration over the R and S domains, which is a complicated and tedious process. A simplified calculation method, the first order and second moment method, has been developed to meet this need. The method uses the statistics of the basic independent random variables, such as R and S; to calculate the approximate statistics of the performance function variable, in this case $Z = R - S$, so as to bypass the complicated integration process. According to the principle of statistics, the performance function $Z = R - S$ Is also a normally distributed random variable, if both R and S are independent random variables under normal distribution? If the probability density function (PDF) and the cumulative probability function (CPF) of Z are denoted as fz(Z) and Fz(z) respectively, the liquefaction probability Pf then equals the probability of $Z = R - S \langle 0$. Hence

$$P_l = \int_{-\infty}^{0} f_z(z)dz = F_z(0) \quad (10)$$

This is shown in Fig. 12. If the mean values and standard deviations of R and S are μ_R, μ_s, σ_R, σ_s ,according to the first order and second moment method, the mean value μ_z , the standard deviation δ_z , and the coefficient of variation δ_z , of Z; can be derived as follows [17][18]:

$$\mu_z = \mu_R - \mu_S \quad (11)$$

$$\sigma_Z = \sqrt{\sigma_R^2 + \sigma_S^2} \quad (12)$$

$$\delta_Z = \frac{\mu_Z}{\sigma_Z} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \quad (13)$$

The statistics for the performance function Z can be simply calculated by above Eqs, using statistics for the basic variables R and S: This shows the advantage of the first order and second moment method. The reliability index β is defined as the inverse of the coefficient of variation δ_z , and is used to measure the reliability of the liquefaction evaluation results. β Is expressed as

$$\beta = \frac{1}{\delta_z} = \frac{\sigma_z}{\mu_z} \quad (14)$$

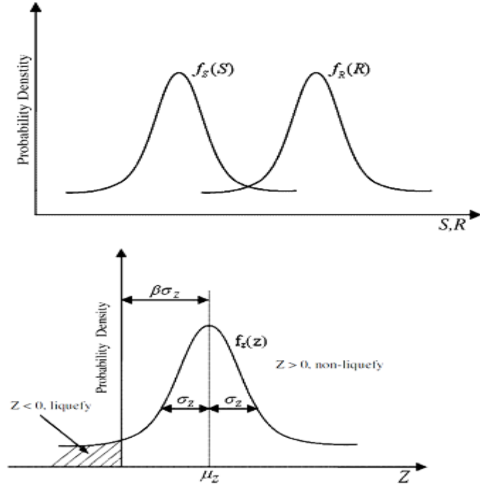


Figure 12. Probability density distribution for the liquefaction performance function

In Fig. 12 the liquefaction probability is indicated by the shaded tail areas of the PDF $f_z(z)$ of the performance function Z [20][21]: Since $\mu_z = \delta_z \beta$ the larger the, the greater the mean value μ_z and the smaller the shaded area and the liquefaction probability P_L .This means that β has a unique relation with P_L and can be used as an index to measure the reliability of the liquefaction evaluation.

Since the normal distribution is the most important and the simplest probability distribution, we first assume that R and S are independent variables with a normal distribution to demonstrate the process of the reliability analysis.

Based on this assumption, the performance function $Z = R - S$ is also in a normal distribution of $Z \sim (\mu_z, \delta_z^2)$. By placing the PDF of Z, we obtain the following liquefaction probability P_L:

$$P_l = \int_{-\infty}^{0} f_z(z)dz = \int_{-\infty}^{0} \frac{1}{\sqrt{2\pi}\delta_z} e^{-\frac{1}{2}\left(\frac{z-\mu_z}{\delta_z}\right)^2} dz \quad (15)$$

The above equation can be rewritten as

$$P_l = \int_{-\infty}^{-\frac{\mu_z}{\sigma_z}} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dz = \phi\left(-\frac{\mu_z}{\sigma_z}\right) \quad (16)$$

Here ϕ is the cumulative probability function for a standard normal distribution. Since $\beta = \mu_z / \sigma_z$, then

$$P_l = \phi(-\beta) \quad (17)$$

$$P_l = 1 - \phi(\beta) \quad (18)$$

The probability distribution of the basic engineering variables is usually slightly skewed, so they cannot be reasonably modeled by a normal distribution function. It has been found that most of the basic variables in engineering areas can be described more accurately by a log-normal

Distribution model, such as that proposed by Rosen Blueth and Estra [19]. In this research, we also found that the CRR and the CSR data are more close to log-normal distributions, therefore, assumed that R (CRR) and S (CSR) are lognormal distributions. Based on this assumption, the liquefaction performance function is defined as $z = \ln(R/S) = \ln R - \ln S$ since the state of $\ln(R/S) = \ln 1 = 0$ is equivalent to the state of $R/S = 1$ or $R - S = 0$, the limit state of liquefaction. Then, the reliability index β and the liquefaction probability P_L ; can be expressed as [21] [22]

$$\beta = \frac{\mu_z}{\sigma_z} = \frac{\mu_{\ln R} - \mu_{\ln S}}{\sqrt{\sigma_{\ln R}^2 + \sigma_{\ln S}^2}} = \frac{\ln\left[\frac{\mu_R}{\mu_S}\left(\frac{\delta_S^2 + 1}{\delta_R^2 + 1}\right)^{1/2}\right]}{\left[\ln\left(\delta_R^2 + 1\right)\left(\delta_S^2 + 1\right)\right]^{1/2}} \quad (19)$$

$$P_l = \phi(-\beta) = 1 - \phi(\beta) \quad (20)$$

For liquefaction analysis using reliability method, values of the random variables (a_{max}/g); Yd.; MSF; $(N_1)_{60}$ are generated consistent with their probability distribution and the function of the CSR or CRR is calculated for each generated set of variables. The process is repeated numerous times and the expected value and standard deviation of the function of the CSR or CRR are calculated. Different probabilities of liquefaction ranging from 18–100% are obtained using the reliability model as shown in Table XI.

TABLE XI. TREE DIFFERENT CASES CONSIDERED FOR RELIABILITY INDEX AND PROBABILITY CALCULATION

Row	Depth(m)	β		PL (%)
1	2	Case1	0.68	26.5
		Case2	-0.23	59.4
		Case3	-0.3	61.9
2	4	Case1	-1.4	93
		Case2	-1.35	91.2
		Case3	0.48	31.3
3	6	Case1	-9.4	100
		Case2	-0.06	52
		Case3	-6.91	100
4	8	Case1	-1.02	84.6
		Case2	-1.13	87.2
		Case3	-0.52	70
5	10	Case1	-1.34	91
		Case2	-0.65	74
		Case3	-1.17	88
6	12	Case1	-1.2	88.5
		Case2	-0.04	51
		Case3	0.57	28
7	14	Case1	-0.05	52.2
		Case2	-1.38	91.7
		Case3	-0.5	70.6
8	16	Case1	-1.19	88.4
		Case2	-0.83	79.8
		Case3	-2.15	98.4
9	18	Case1	-0.2	60.7
		Case2	0.26	39.5
		Case3	-0.31	62.2
10	20	Case1	0.89	18
		Case2	-	-
		Case3	-0.25	60

VI.FURTHER DISCUSSION DO THE RESULTS

Evaluation potential of liquefaction in soil of Babol city in Iran is very important issue since soil of some areas in made of sand**.** In this paper, we collect about 300 data from different lab in Babol city and analyzed that data with four approaches which describe at above. We divided Babol city to three part and evaluation potential liquefaction in each section and choice one borehole log based on engineer adjudication from each part and do analyze. Table 1 show a summary of this reliability analysis for all cases in the northwest of Babol city at the different depths where soil performance against liquefaction was reported. For each of these cases, the CSR, CRR, safety factor with three approach and the probability of liquefaction (PL) are calculated continuously at all depths so that a profile of PL can be draw. A liquefiable sandy layer exists from a depth of 2–22 m. The soil parameters and the factors of safety against liquefaction using a deterministic method and probability of liquefaction (P_L) are shown in above tables. Fig. 13 shows a sample output of the PL profile, along with the Fs1 and Fs2 as well as OCDI profiles and the input SPT profiles. Draw of the Fs1 and Fs2 profiles, such as those shown in Fig. 13, are quite useful, as they show which layers are likely to liquefy. However, this assessment of the liquefaction potential is essentially deterministic. Because of the uncertainties involved in the calculation of CSR and CRR, such a deter-ministic approach is not always appropriate. The draw of the PL profile, as shown in Fig. 13, offers an alternative on which engineering decisions may be based.

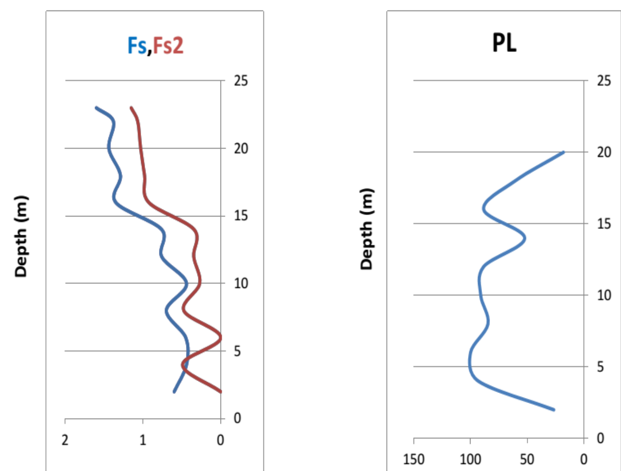


Figure 13. comparison of safety factors and probability of liquefaction related to AMIRKABIR-BABOL site

With this profile, the engineer can determine which layers are sensitive to liquefaction from the viewpoint of an acceptable risk level. This advantage is also observed in Table XI. For example, in the case of 1 at the depth of 2 m, the comparison of calculated Seed At all and the highway bridge of Japan method suggests that there would be liquefaction since CRR > CSR (albeit slightly). On the other hand, OCDI approach shows that the soil is in the 3 area and the possibility of liquefaction is low. However, the field observation indicates the occurrence of liquefaction. The probability of liquefaction for this case is 26.5, which suggests that liquefaction may not be possible. Similar observation is found in the case of 5. In the case of 8, the Seed method yields an Fs1=0.58 and OCDI method shows the soil is in four areas, which suggests that liquefaction will not occur. However, the field observation indicates the highway bridge of Japan method shows there would be liquefaction. For this case, the result of the probability analysis (PL = 52.2) does not output a credible support of the occurrence of liquefaction.

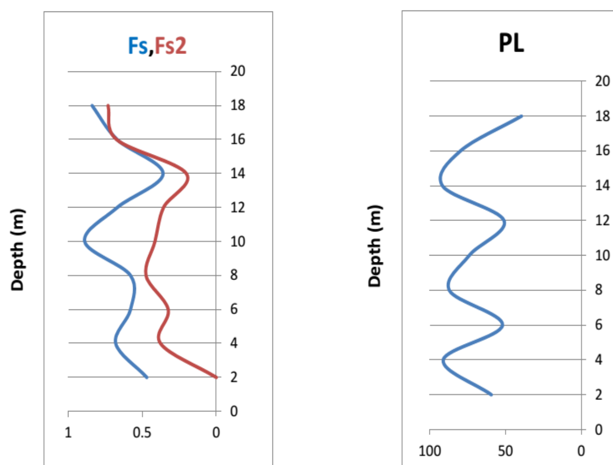


Figure 14. comparison of safety factors and probability of liquefaction related to Motahary- Babol site

Fig. 14 shows a sample output of the PL profile, along with the Fs profiles and the input SPT profiles in the second area. Draw of the Fs profiles, such as those shown in Fig. 14(Fs), are quite useful, as they show which layers are likely to liquefy. In the case of 1 at the depth of 1.2 m, the comparison of calculated OCDI approach shows that the soil is in the 3 area and the possibility of liquefaction is low. On the other hand, the highway bridge of Japan method suggests that liquefaction will not occur (with Fs=1.38). However, the field observation indicates the occurrence of liquefaction. The probability of liquefaction for this case is 54.9, which suggests that the possibility of liquefaction is low. In the case of 6, OCDI method shows the soil is in four areas, which suggests that liquefaction will not occur. However, the field observation indicates the highway bridge of Japan method shows there would be liquefaction. Occurrence of liquefaction. For this case, the result of the probability analysis (PL = 52.2) does not output a credible support of the occurrence of liquefaction. Similar observation is found in the case of 6, however in this case the result of the probability analysis is very high, which is 91.7%, and it shows that liquefaction will occur.

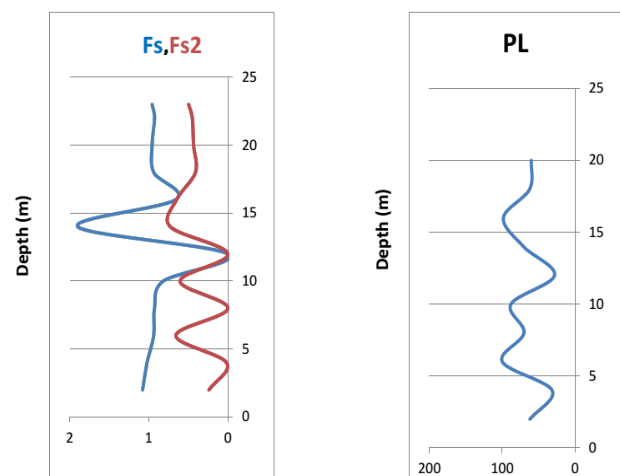


Figure 15. comparison of safety factors and probability of liquefaction related to Modares- Babol site

In the case of 1 at the depth of 2 m, the comparison of calculated the highway bridge of Japan method suggests that there would be liquefaction, which the safe factory related to this approach is 0.24. On the other hand, OCDI approach shows that the soil is in the 4 area and the possibility of liquefaction is impossible. However, the field observation indicates the occurrence of liquefaction. The probability of liquefaction for this case is 61.9, which suggests that the Liquefaction incidence and Liquefaction non-occurrence are equally probable. In the case of 6 OCDI method shows the soil is in four areas, which suggests that liquefaction will not occur. However, the field observation indicates the highway bridge of Japan method shows there would be liquefaction. For this case, the result of the probability analysis (PL = 28) the Liquefaction incidence is unlikely. In a reliability analysis of soil liquefaction potential, it is necessary to define a limit state that separates liquefaction from non-liquefaction. In this paper, for the all data, the boundary curve in the Standard Penetration Test (SPT)-based simplified method. First of all the amount of CSR is calculating for each depth and the amount of tension on the modified standard penetration is plotted. When the process is repeated for different depth at different sites, a set of points the modified standard penetration and cycle

stress ration is formed. Viewing the set of ordered pairs, each with specific characteristics (number of SPT, cycle stress ration and liquefaction condition specified) are caused relatively clear border between liquefaction and non-liquefaction points are formed (Shape 16).

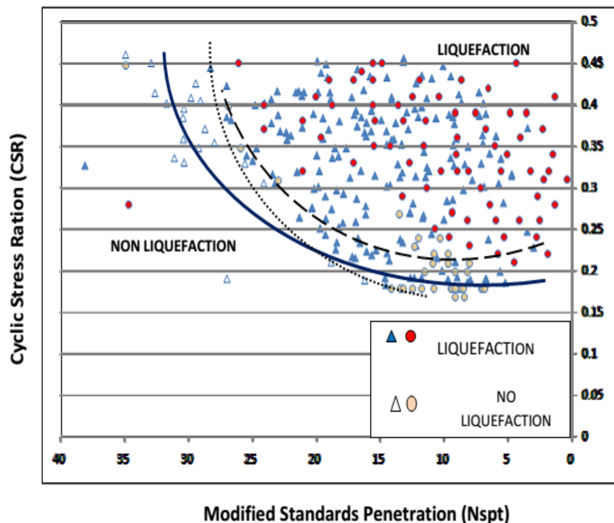


Figure 16. limit state (boundary between liquefaction and non-liquefaction states)

CONCLUSIONS

A new framework for the reliability analysis of liquefaction potential has been presented in this paper. Excellent results have been obtained in terms of being able to assess the liquefaction potential in a more rational way. The method has been implemented in a spreadsheet and, given the SPT profiles; the profile of the probability of liquefaction can be easily obtained. This method has the potential of becoming a practical tool for the engineer involved in the assessment of liquefaction potential. The developed spreadsheet modules are available from the writers.

Regarding to the performed comparisons between the proposed (suggested) method and crucial (certain) analysis based method in this research, the efficiency of the proposed (suggested) method is well shown and it can be applied as a functional tool for engineers usage (application).

In this research, it was determined that confidence coefficient bigger (greater) and less (smaller) than 1 doesn't mean safety and/ or liquefaction in cadence for liquefaction and for assuring about liquefaction probability, reliability based method analysis should be used.

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